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14. ABSTRACT
When Hurricane Katrina passed over southern Florida, Florida Bay and the West Florida Shelf, and into the Gulf of Mexico, empirically derived chl a increases were observed in the Tortugas Gyre circulation feature, and in adjacent waters. Analysis of the empirically derived chl a increase within the gyre has been primarily attributed to initiation of a phytoplankton bloom promoted by nutrients upwelled by Katrina's winds. Detailed analysis of inherent optical properties derived from remotely sensed radiances, however, indicated the interaction of Katrina with shallow coastal and shelf waters likely entrained waters with higher concentrations of chromophoric dissolved organic matter (CDOM) into the gyre circulation, augmenting the chl a signal. Storm-induced upwelling would also transport optically active CDOM to the surface. Increases in empirically derived chl a in the Florida coastal waters influenced by Katrina's winds were therefore partly due to increased absorption by CDOM. This analysis indicates that elevated empirically derived chl a in hurricane-influenced waters should not be unambiguously attributed to increased phytoplankton productivity, particularly in an optically complex coastal environment.

15. SUBJECT TERMS
chylorophyll, dissolved organic matter, marine vegetation, optics, plankton, remote sensing, sea coast, sea surface

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Interaction of Hurricane Katrina With Optically Complex Water in the Gulf of Mexico: Interpretation Using Satellite-Derived Inherent Optical Properties and Chlorophyll Concentration

James Acker, Paul Lyon, Frank Hoge, Suhung Shen, Mitchell Roffer, and Greg Gawlikowski

Abstract—When Hurricane Katrina passed over southern Florida, Florida Bay and the West Florida Shelf, and into the Gulf of Mexico, empirically derived chl a increases were observed in the Tortugas Gyre circulation feature, and in adjacent waters. Analysis of the empirically derived chl a increase within the gyre has been primarily attributed to initiation of a phytoplankton bloom promoted by nutrients upwelled by Katrina's winds. Detailed analysis of inherent optical properties derived from remotely sensed radiances, however, indicated the interaction of Katrina with shallow coastal and shelf waters likely entrained waters with higher concentrations of chromophoric dissolved organic matter (CDOM) into the gyre circulation, augmenting the chl a signal. Storm-induced upwelling would also transport optically active CDOM to the surface. Increases in empirically derived chl a in the Florida coastal waters influenced by Katrina's winds were therefore partly due to increased absorption by CDOM. This analysis indicates that elevated empirically derived chl a in hurricane-influenced waters should not be unambiguously attributed to increased phytoplankton productivity, particularly in an optically complex coastal environment.

Index Terms—Chlorophyll, dissolved organic matter, marine vegetation, optics, plankton, remote sensing, sea coast, sea surface.

I. INTRODUCTION

HURRICANE winds are known to have substantial effects on the upper ocean environment, where wind stress mixes the surface layer, deepens the mixed layer, and storm circulation creates divergence in the storm center. The result of divergence is local upwelling, which will transport water from depth to the surface [1], [2]. A common signature of these processes will be reduction of sea surface temperature (SST) and increase

of nutrient concentrations at the surface; the latter effect may foster a phytoplankton bloom [3], [4].

Deeper waters transported to the surface, particularly by vertical mixing [5], [6], will normally also contain chromophoric dissolved organic matter (CDOM) with a significantly higher absorption coefficient than photochemically degraded CDOM present in the undisturbed prestorm upper mixed layer [7], [8]. The default NASA chlorophyll concentration (chl a) algorithms are empirical algorithms parameterized by radiance ratios, which are strongly driven by the total absorption of all optically active constituents in the observed waters. Chl a retrievals derived from algorithms parameterized with data sensitive to total absorption coefficients can therefore show an increase in chl a if there is an increase in the level of any of the absorbing constituents, notably CDOM. Thus, the potential influence of highly absorbing CDOM should always be considered when increased chl a in hurricane wakes is observed in standard ocean color data products [9], and this increase should not be interpreted as an unambiguous indication of living phytoplankton growth.

Interactions of hurricane winds with shallow coastal waters complicate interpretation of a storm-induced chl a signal. The first complicating factor is higher coastal water chlorophyll concentrations, which will increase chl a offshore when coastal waters are wind-advected to the open ocean. Observation of increased chl a offshore following storm passage may thus be partly and simply due to transport of higher chl a waters. The second complicating factor is suspension of bottom sediments, but the sediment signal can be distinguished from chl a based on either reflection in nonabsorbing bands and backscattering. A factor which is more difficult to distinguish is higher CDOM concentrations, particularly the potential release of CDOM from wind-suspended coastal sediments followed by offshore advection [10].

When Hurricane Katrina passed over the southern Florida peninsula, the southern West Florida Shelf, and the outer margins of Florida Bay, storm winds created a complex interaction between shallow coastal waters and open ocean waters. This hurricane interaction also influenced the Tortugas Gyre, a recognized circulation feature in the southern Gulf of Mexico induced by the flow of the Loop Current [11]. Interaction with Katrina's winds increased chl a and CDOM absorption within the Tortugas Gyre, making the gyre visible in chl a images.

In the analysis presented here, an in-water radiative transfer optical model (also termed a "semi-analytic" model) operating

on reflectances acquired by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) is used to calculate inherent optical properties (IOPs). The IOPs calculated are the phytoplankton absorption coefficient (a_{ph}), CDOM and detrital absorption coefficient (a_{dg}), and total constituent backscattering coefficient (b_{bt}). The use of IOPs in the study of oceanic eddies has been reported [12] and these same methods are applied herein.

II. DATA

Initial analysis of SeaWiFS eight-day Level 3 data was performed using the Goddard Earth Sciences Data and Information Services Center Interactive Online Visualization ANd aNalysis Infrastructure (Giovanni) [13]. Giovanni was also used to generate a chl a time series for the study region. Corresponding SeaWiFS Level 1A and MODIS Level 1B data files were acquired from the Ocean Biology Processing Group Level 1A and 2 data browsing system. The SeaWiFS OC4V4 algorithm generates the chl a retrievals described in this letter.

The SeaWiFS and MODIS data were processed by linear matrix inversion of an oceanic radiance model [14]–[18]. Absorption coefficients a_{ph}, a_{dg}, and backscattering coefficient b_{bt} at each invertible pixel are binned into 0.01 square degree bins. If a bin contains more than one valid pixel for a single day of orbits from either SeaWiFS or MODIS, the IOPs within those pixels are averaged together to create a composite grid. Any empty bins within the composite grid are filled with a distance-weighted kernel with a bin radius of 0.03°, which is approximately 4.5 km at the latitudes under study. Validation studies [14], [18] indicate that current atmospheric correction algorithms are sufficient to allow accurate IOP retrievals.

QuikSCAT Level 3 daily wind data were acquired from the Jet Propulsion Laboratory Physical Oceanography Distributed Active Archive Center. SST data analysis was performed by ROFFS utilizing infrared (IR) bands from both National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (AVHRR) and MODIS-Terra and MODIS-Aqua, the latter acquired from the University of South Florida Institute for Marine Remote Sensing. Computerized rectification and calibration is performed on all images, which are then rerectified manually and recalibrated using buoy data from National Data Buoy Center. Both short-term (3, 6, 12, and 24 h) warm water composites and single images are utilized. Visible band data from MODIS is integrated into the image sequence to facilitate visualization of ocean boundaries not readily apparent in the IR data.

Hurricane Katrina latitude/longitude position data were obtained from the Unisys Weather web site (http://weather.unisys.com).

III. RESULTS AND DISCUSSION

Hurricane Katrina first made landfall on the continental United States on the southeastern coast of Florida [19], [20]. On August 25, Katrina intensified to hurricane strength a few hours before landfall. The storm weakened to tropical storm strength over land before entering the Gulf of Mexico just north of Cape Sable on the morning of August 26. Storm surge in the Cape Sable region was 1.3 m [20]. The storm rapidly reintensified to hurricane strength on August 26, while the eye was over the
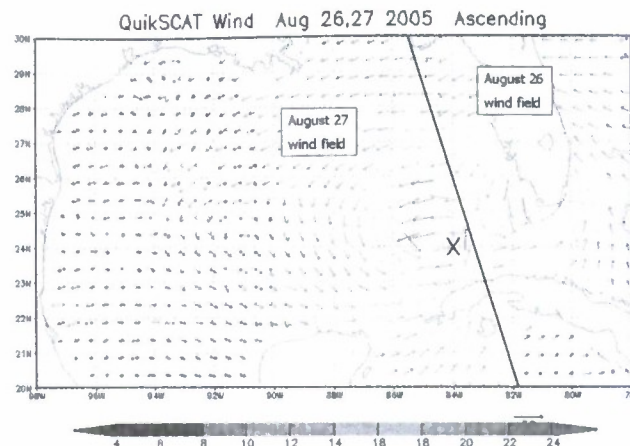

Fig. 1. QuikSCAT sea surface wind vectors for August 26 and August 27, 2005. In August 26, Katrina's winds along the West Coast of Florida are observed to progress from northerly over Florida Bay to northeasterly, with lesser strength, moving northward along the coast. In August 27, the strong wind circulation of Katrina is clearly seen, with the winds at the time of observation circulating around the eye, near the location of the optical feature designated with arrow #1 in Fig. 2. The diagonal black line marks the edge of the August 26 QuikSCAT scan swath.

northwestern margins of Florida Bay. On August 27, Katrina's southwesterly movement positioned it approximately due west of Key West and the Dry Tortugas. Katrina then proceeded in a northwesterly direction toward its eventual catastrophic landfall on the northern Gulf Coast.

Due to fortuitous positioning of observational swaths, the QuikSCAT scatterometer captured wind speed vectors for Hurricane Katrina (Fig. 1) on both August 26, ∼6:45 A.M. EDT (10:45 UTC), and August 27, ∼8:00 A.M. EDT (12:00 UTC). On August 27, when observed by QuikSCAT, the eye of Katrina was located at approximately 85° W, 24° N. The "X" shown at 84° W and 24° N in Fig. 1 marks the approximate center of the optical feature which will be described subsequently.

Examination of SeaWiFS eight-day Level 3 chl a data in Giovanni for the period August 29–September 5 clearly showed the elevated chl a feature at 84° W, 24° N [9]. This study suggested a contribution of optically active constituents from coastal waters to the chl a signal. Fig. 2(a) is an image derived from merged SeaWiFS and MODIS Aqua chl a data using data from August 21 to August 30, 2005. SeaWiFS chl a and MODIS Aqua chl a data are a binned average of all observations acquired during the ten-day binning period in the same manner as the IOP images.

The elevated chl a concentration feature prominent in the image, centered at 84° W, 24° N (indicated by arrow #1) on the left-hand side of Katrina's track, is located within the Tortugas Gyre. Fig. 2(b) is an SST analysis by ROFFS of the preexisting conditions in this region, confirming the location of the Tortugas Gyre during the period August 20–21, 2005. Fig. 3(a) shows the bin-averaged IOPs a_{ph}, a_{dg}, and b_{bt} derived from SeaWiFS and MODIS Aqua data over the period August 19–23, 2005 for the region prior to the passage of Katrina. Tortugas Gyre was not apparent in the visible spectrum data.

Initial examination of the Giovanni-derived image also revealed an elevated chl a feature [indicated by arrow #2 in Fig. 2(a)] appearing to emanate from the West Florida shelf and connecting to the Tortugas Gyre area. Uncertainty about the composition of the optical features induced us to undertake a detailed IOP analysis of the daily SeaWiFS and MODIS
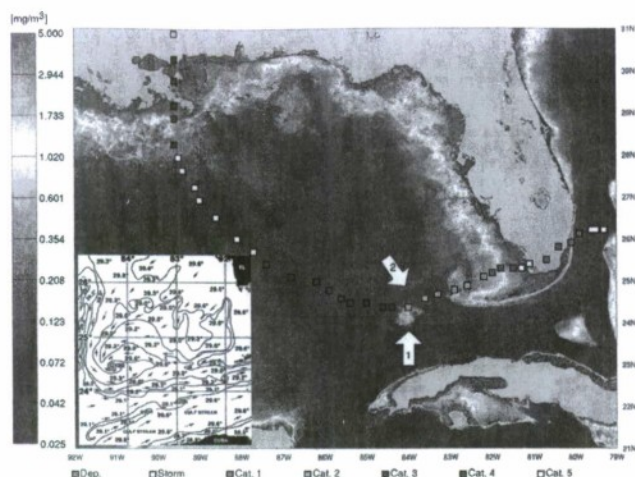
Fig. 2. (a) Merged SeaWiFS and MODIS chl a image of the Gulf of Mexico for the period August 21–30, 2005. Katrina storm positions at 2-h intervals with color-coded storm intensity are superimposed. Arrow #1 indicates the circular elevated chl a feature in the position of the Tortugas Gyre [Fig. 2(b)]. Arrow #2 indicates the elevated chl a connecting from the West Florida Shelf to the Tortugas Gyre. Arrow #3 indicates Cay Sal Bank. (b, inset) Pre-Katrina SST analysis (based on AVHRR and MODIS data) from August 20 to 21, 2005, indicating the position of the Tortugas Gyre.
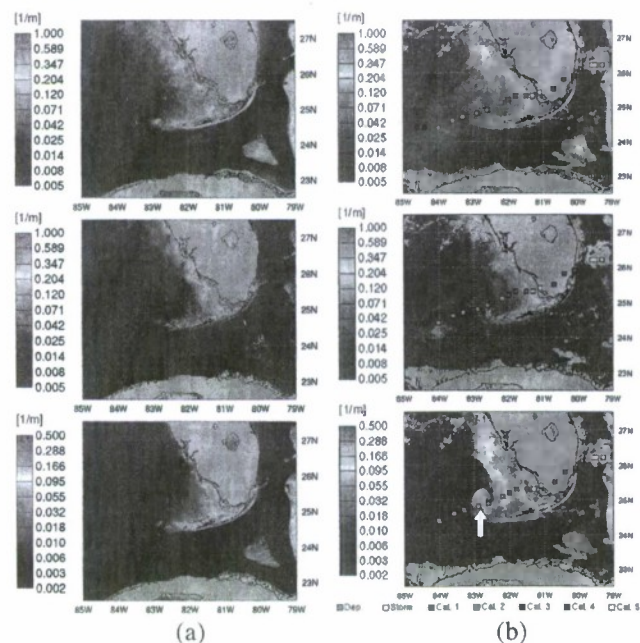

Fig. 3. (a) (Top) a_{dg}, (center) a_{ph}, and (bottom) b_{bt} bin-averaged IOP images for the period August 19–23, 2005. The Tortugas Gyre is not visible in this data prior to the passage of Katrina. (b) (Top) a_{dg}, (center) a_{ph}, and (bottom) b_{bt} bin-averaged IOP images for the period August 30–31, 2005. (3b, top) Elevated a_{dg} is observed extending from the West Florida Shelf toward the Tortugas Gyre and in the Gyre. (3b, center) Elevated a_{ph} is observed in the Tortugas Gyre, but a_{ph} is not significantly elevated in the feature extending from the shelf. (3b, bottom) Significantly elevated b_{bt} is observed along the West Florida Shelf and in Florida Bay, particularly a lobate feature designated by the arrow, indicating movement of suspended sediments.

radiance data, as optically complex waters commonly provide falsely elevated chl a concentration retrievals [21].

A detailed analysis of the upper ocean response to Hurricanes Katrina and Rita [22] included analysis of sea surface height, SST, ocean surface wind, and chl a data, as well as ocean GCM results. This analysis clearly indicated that SST within the Tortugas Gyre decreased, and also noted that MODIS chl a

within the Tortugas Gyre increased. Because decreased SST can be interpreted as a proxy for the transport of nutrients from depth to the surface by storm-induced upwelling, decreased SST and increased chl a were interpreted as indicative of a phytoplankton bloom. A separate study [23] also attributed the elevated chl a to a phytoplankton bloom.

Fig. 3(b) shows bin-averaged a_{ph}, a_{dg}, and b_{bt} derived from SeaWiFS and MODIS Aqua data for the region from August 30 to 31, 2005. Fig. 3(b) is key to our interpretation of this event. a_{dg} (top panel) is elevated ($\sim$0.12 m^{-1}) both in the Tortugas Gyre and most notably in the feature [#2 in Fig. 2(a)] emanating from the coast and connecting to the gyre circulation. Phytoplankton absorption coefficient a_{ph} (center panel) is also elevated in both locations, but is clearly not as high close to the coast where a_{dg} is elevated. Total constituent backscattering coefficient b_{bt} (bottom panel) is very high in outer Florida Bay, indicative of suspended sediments. Note that there is also an elevated a_{dg} feature on the northeast corner of Cay Sal Bank.

In the top panel of Fig. 3(b), there are three significant areas of increased a_{dg}, indicative of CDOM transport: the large feature extending from the West Florida Shelf; small areas south of the middle Florida Keys; and plume with high a_{dg}, low a_{ph} and low b_{bt} emanating from Cay Sal Bank and extending northeastward. b_{bt} [bottom panel, Fig. 3(b)] clearly shows wide areas with a large increase of backscaterring coefficient in outer Florida Bay and along the West Florida coast, likely due to sediment resuspension. This figure indicates where suspended sediments had the most significant impact on the optical characteristics of the water column. Rapid settling of particles limits the transport distance and optical signal in waters further from the shelf edge.

The increased values of a_{dg} and a_{ph} in the Tortugas Gyre shown in Fig. 3(b) indicate that the derived chl a value [Fig. 2(a)] is mostly likely due to the optical mixing of absorption by CDOM and absorption by phytoplankton chlorophyll. An elevated a_{dg} feature, with very low a_{ph}, is observed emanating from the West Florida Shelf and connecting into the outer gyre circulation. This feature indicates that some highly absorbing coastal water transported off the shelf by Katrina's winds (Fig. 1) was entrained in the gyre circulation. Wang and Oey [24] indicate that Katrina's winds induced transient surface currents with velocities of 1–1.5 m/s with a pattern generally following the wind. These current velocities translate to an advection distance over 24–36 h of 90–195 km, which is more than sufficient to transport West Florida Shelf waters into the Tortugas Gyre circulation. Note that there is no significant contribution to the optical characteristics of these waters from suspended sediments west of the shelf margin.

A two-day SeaWiFS/MODIS Aqua composite of IOP data for September 1–2 showed some seaward movement of the high a_{dg} feature emanating from Cay Sal Bank. In the Tortugas Gyre, a_{ph} and a_{dg} were diminished. Data for the next several days was limited due to cloud cover. SeaWiFS and MODIS IOP retrievals from September 6 to 7 showed only a faint persistence of the absorption coefficients a_{ph} and a_{dg} in the Tortugas Gyre.

The potential for bottom sediments to release significant quantities of CDOM must be examined. Release of nutrients from bottom sediments following a strong storm has been observed, with markedly increased nutrient concentrations above the bottom layer [25]. On the northeastern U.S. coast, optical

transects (surface to benthos) indicated that over extended periods, episodic CDOM variability was primarily dominated by storm events which caused sediment resuspension [26]. In particular, CDOM concentrations in anoxic sediments are very high, making them important coastal sources of highly absorbing CDOM if sediments are mobilized by storms. This observation is supported by mesocosm experiments demonstrating bacterial and sediment CDOM production [27].

Katrina's passage over the southwestern Florida coast and into the Gulf of Mexico induced significant sediment resuspension in shallow coastal and shelf waters. Sediment suspension mobilized benthic CDOM and benthic nutrients. Northeasterly winds advected coastal waters containing CDOM, elevated nutrient concentrations, and higher phytoplankton concentrations into the southeastern Gulf of Mexico.

A portion of the advected coastal waters were subsequently entrained in the Tortugas Gyre circulation. CDOM and nutrient concentrations were elevated by upwelling within the gyre. The increased chl a signal detected in the Tortugas Gyre in August 30 is thus interpreted as a mixed signal from increased CDOM absorption and increased phytoplankton chlorophyll absorption. Elevated chl a values are localized in the gyre circulation, indicating the importance of the circulation feature to both collect transported shelf CDOM and shelf phytoplankton, and to enhance upwelling. Upwelling resulted in higher nutrient concentrations (supporting phytoplankton growth) [22] as well as higher concentrations of upwelled CDOM. A normalized-water leaving radiance minimum at 443 nm [23] indicates the presence of elevated chl a, likely due to increased phytoplankton growth, as does increased a_{ph} in this letter. This spectral characteristic does not, however, preclude a contribution to the optical properties of the gyre from CDOM.

One of the significant aspects of this letter is the identification of the Tortugas Gyre circulation with visible-range remote sensing. Previous studies [22], [23] addressed the presence of the gyre, but did not provide historical oceanographic context. The Tortugas Gyre is considered a quasi-permanent circulation feature which can vary in position significantly [28] and is usually oligotrophic [29]. Under normal conditions, the Loop Current and Tortugas Gyre in this region are waters of exceptionally high optical clarity (euphotic depths ranging from 70 to 90 m). This optical condition is demonstrated by the presence of photosynthetic coral communities at approximately 60-m depth on Pulley Ridge, which is located just east of 84° W between 24.5° and 26° N [30]. Pulley Ridge lies directly north of the approximate center of the Tortugas Gyre location on August 30. Fig. 4 shows a time series of the eight-day SeaWiFS chl a values for the period January 1998–December 2007 for the location of the Tortugas Gyre at the time of Katrina's passage [Fig. 2(b)]. This analysis confirms our observations that for the ten-year period studied, the single time the Tortugas Gyre was visible in the IOP imagery was following the passage of Katrina.

Fig. 5 shows difference images of ten-day SeaWiFS/MODIS Aqua composites from August 24 to September 4 for chl a [Fig. 5(a)]; detrital and dissolved organic matter absorption coefficient a_{dg} [Fig. 5(b)]; phytoplankton absorption coefficient a_{ph} [Fig. 5(c)]; and backscattering coefficient b_{bt} [Fig. 5(d)]. Fig. 5(a) shows an increase in chl a due to Katrina's influence ranging from ~0.02 to > 2.5 mg/m^3. Analysis of Fig. 5(b)–(d) shows that most increases of radiance ratio-derived chl a prod-
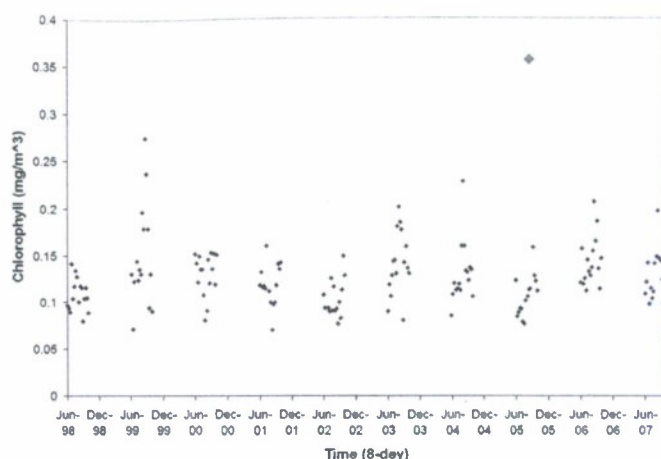

Fig. 4. Giovanni-generated SeaWiFS eight-day chl a time series for the Tortugas Gyre location in Fig. 2(b) (bounded by 24.0° N and 24.5° N latitude, 83.75° W and 84.25° W longitude) at the time of Katrina's passage, showing only peak hurricane season months (June–September) for clarity. This figure indicates for this location, the passage of Katrina caused the highest values of remotely sensed chl a detected over the SeaWiFS mission (orange diamond).
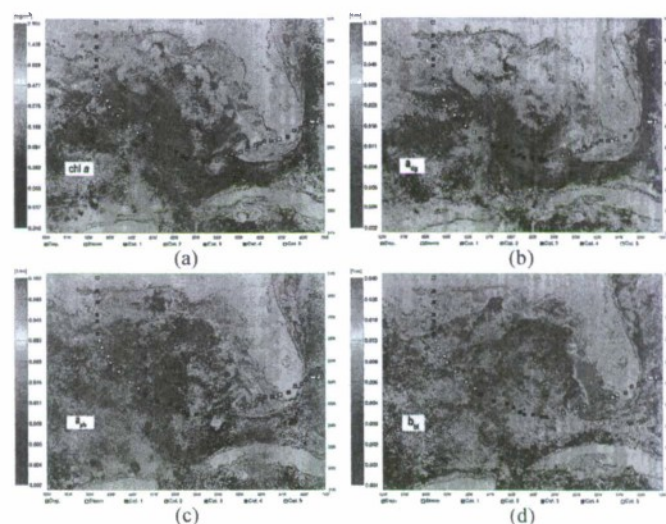

Fig. 5. Difference images of SeaWiFS and MODIS-Aqua chl a and the IOPs a_{dg}, a_{ph}, and b_{bt} between the ten-day composite ending in August 24 to the ten-day composite ending on September 4, 2005. In each image, all bins without an increase of a parameter from August 24 to September 4 are masked with gray pixels. (a) Increased chl a is observed on the West Florida Shelf, in the feature connecting the Tortugas Gyre to the West Florida Shelf, and in the Tortugas Gyre. (b) a_{dg} shows significant areas of increase on the West Florida Shelf, in the feature connecting to the Tortugas Gyre, in the Gyre itself, and under the track of Katrina extending toward Louisiana. (c) a_{ph} is elevated in the Tortugas Gyre and in a small area to the north, but is not increased in the feature connecting to the shelf, where a_{dg} is elevated. (d) Marked elevation of b_{bt} along the southern West Florida Shelf and in outer Florida Bay is observed, indicative of sediment suspension and sediment transport. A small area of increased b_{bt} just south of the central Gyre circulation could indicate where phytoplankton responded to the upwelled nutrients by increasing their intracellular chlorophyll concentrations.

ucts are actually due to increase in a_{dg}. In the a_{dg} track of Katrina toward Louisiana [Fig. 5(b)], the region of elevated a_{dg} northwest of the gyre, apparently due solely to CDOM transported from deeper waters, provides a qualitative visual indication of the contribution of CDOM adsorption to the total absorption within the Tortugas Gyre. Note that the b_{bt} did not change significantly in the oligotrophic central Gulf of Mexico, so Fig. 5(d) has more masked pixels.

IV. CONCLUSION

This analysis detected a significant absorption signal attributable primarily to CDOM in a feature extending from the southern West Florida Shelf into the outer circulation of the Tortugas Gyre. The analysis also indicated major sediment resuspension in outer Florida Bay and on the southern shelf, a likely source of benthic CDOM. Detection of CDOM and phytoplankton absorption in the Tortugas Gyre, combined with an oceanographic analysis of the upper ocean response to Katrina in this region, indicates that elevated chl a observed in SeaWiFS and MODIS data products was caused by increased surface concentrations of highly absorbing CDOM combined with elevated phytoplankton chlorophyll concentrations within the gyre. Likewise, the lack of an increase in a_{ph}, along with the increase in a_{dg}, indicates the apparent increase in chl a in waters adjacent to the gyre was most likely a result of the radiance ratio-based algorithms mistaking the increase in a_{dg} absorption as an increase in chl a concentration, because variable absorption by CDOM is imperfectly modeled in the algorithms [31]. (Note that CDOM dominates the absorption represented by a_{dg} in oceanic waters [32].) Upwelled nutrients within the Tortugas Gyre [22], [23] likely promoted both phytoplankton population growth and an increase in the chlorophyll content of individual phytoplankton cells; observation of an increased backscatter signal [Fig. 5(d)] in a small area southwest of the gyre center might indicate the latter process in oligotrophic waters. A question for further research would be to examine the relationship between chl a and maximal phytoplankton growth rates in response to a sudden increase in available nutrients, as would have occurred within the gyre following Katrina's passage.

This analysis demonstrates that increased chl a in satellite remote-sensing data observed subsequent to the passage of a hurricane or tropical storm should not always be exclusively attributed to living phytoplankton chlorophyll, particularly if there is a significant interaction with optically complex coastal waters. It is important, therefore, to consider both regional conditions and the characteristics of individual storms to fully understand the effect of storms on the optical state of the surface ocean. This letter confirms the value of IOPs to ascertain the full set of factors influencing the optical properties of complex coastal waters.

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